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SOIL EVOLUTION

Cryo-Geomorphological Evolution of Soils on Islands of Terekhol Lake, Tyva, Southern Siberia[1]

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Abstract—Specific soils on calcareous lacustrine sediments have been described on the islands in the Terekhol Lake, Terekhol'skaya intermontane trough of the Tuva Upland. The islands themselves originate from frost heaving cycles as shown by their relief and interfacial analysis of litho- and biostratigraphy of dated cores sampled in the bottom of the lake and on the islands. Soils of two altitude-age groups (generations) of islands have been studied. Younger islands (400–1700 cal yrs BP) have relative heights above the lake level below 2.5 m and an active layer 0.6–1.5 m thick. Histic Cryosols (Limnic, Drainic) were found there. Soils are well drained now and have no relation with the lake waters. The central elevated parts of older, and higher islands (4000–5000 cal yrs BP; 2.5–4.5 m, active layer about 1.5 m thick) are under dry-steppe phytocenoses on Calci-Mollic (Histic) Cryosols (Limnic, Calcaric, Gypsiric). The following evolution phases of islands and their soils were reconstructed. The lacustrine sediments were raised from the sedimentation zone to remain in subaerial conditions, where Histic Cryosols were formed. Owing to heaving, an admixture of limnic material was included in them. Further heaving resulted in the isolation of soils from the lake waters, the sedimentation completely stopped, and pedogenesis slowly shifted toward that inherent to well-drained conditions under dry-steppe vegetation. Histic horizons got degraded and transformed to mollic ones, the permafrost table moved deeper, carbonates, gypsum and soluble salts were leached from the upper horizons.

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INTRODUCTION

Specific endemic soils were discovered on lake islands in a remote, poorly studied region in the south of Central Siberia: Terekhol'skaya intermontane trough (51°N, 97°E, 1300 m above sea level) of the Tuva Upland, Tyva Republic. It happened while studying the Holocene history of the trough and the lake within the framework of geo-archaeological project on the Early Medieval Uigurian fortress Por-Bazhyn.

The following phenomena determine the high specificity of described soils.

(1) The soils are permafrost-affected, developed on an unusual parent material: highly calcareous clearly stratified silts, alternating with sandy loams, marl, gyttja and peat. Such substrates in combination with high permafrost table are responsible for the specific water regime, geochemistry, and migration of pedogenic products.

(2) There is a continuous talik[2] under the lake, at the same time the islands have got extremely icy (up to 60–90% of ice) core [10]. They were formed by heaving[3] processes [11]. The emergence of islands is related to cryo-arid phases of the second half of the Holocene. At least two generations of such islands have been identified. Therefore, the islands' soils can be regarded as sequential stages of the Late Holocene evolution related to progressive heaving. Neither the islands, nor their landscapes and soils were described and studied earlier both in this region and in other areas with similar landscapes.

This study is targeted on understanding the genesis and evolution of the discovered soils on the islands. The objectives of this study are the following: 1) to describe the soil forming conditions and specific soils on top topographic level of the islands of two generations; 2) to propose an evolution model for soils of this specific landscape.

[1] The article is published in the original.

[2] Talik is a frost-free area in the permafrost regions, most commonly under any water bodies.

[3] A set of evidences for such origin of islands, details of island formation processes, dating techniques are beyond the scope of this paper.

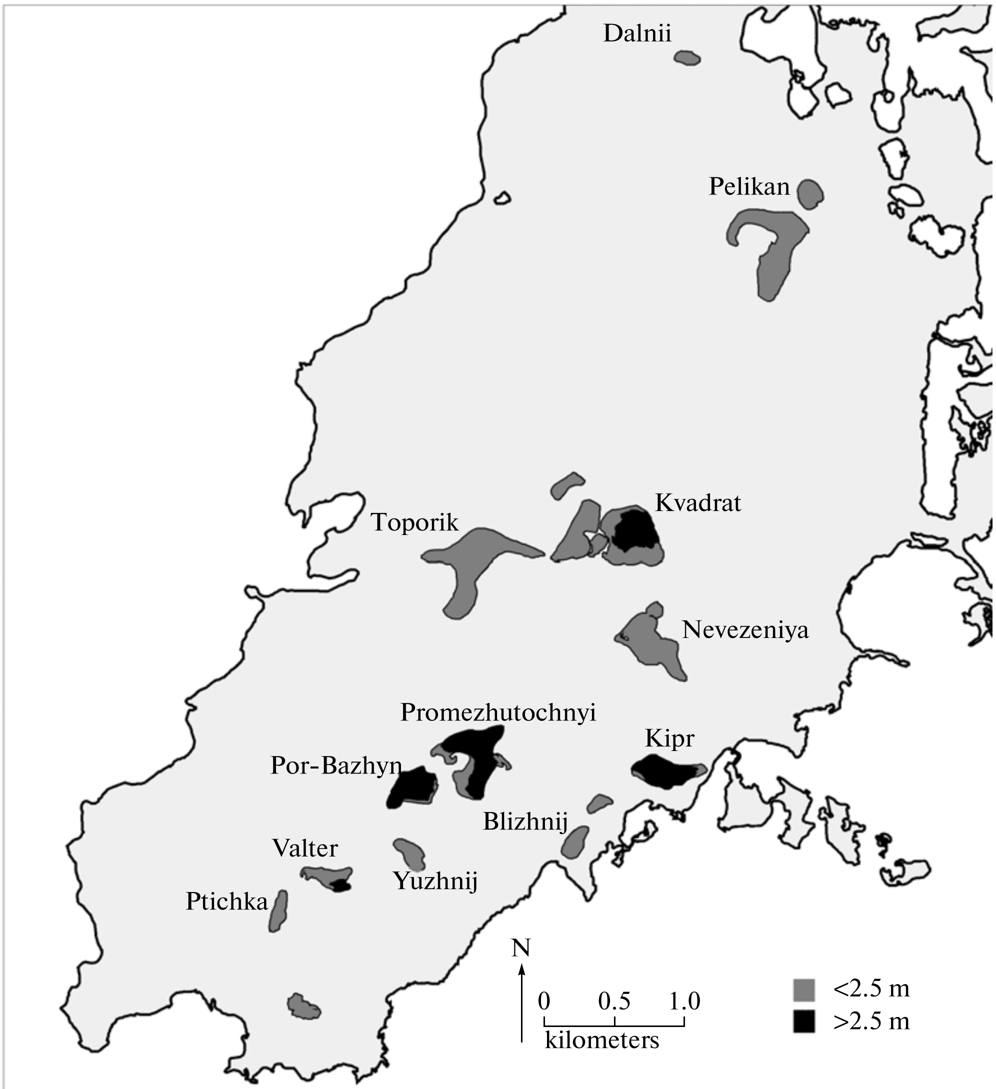

Fig. 1. Groups of island according to their relative height above the lake level, p. 3.

METHODS

The geological composition of islands was examined in pits and rock outcrops at eroded shores. The lacustrine sediments were studied in cores sampled from the bottom by Russian Corer [7] using a wood raft. The topographic profiles were produced for most of islands of the lake, and crossed all their landforms. Representative altitudes of islands and altitudes of soil pits above the lake were determined by a 5X magnifying optical hand level. In each case, the control points at the lake level were measured, which demonstrated the error of elevation measurement less than 0.1–0.2 m.

Detailed field floristic and botanical descriptions were made for Por-Bazhyn and Promezhutochnyi islands. For other islands, vegetation was described using a collection of photographs and synthesized multispectral satellite image LANDSAT 7 (4.10.2002, The Global Land Cover Facility). Only vegetation of the top geomorphologic level is under consideration in this publication. Satellite image was used also for a primary grouping of islands according to their hypothetical altitudes above the lake level.

The soil studies covered twelve islands (Fig. 1). Six of them are young, and low (Dalnii, Pelican, Yuzhnii, Blizhnii, Nevezeniya, Ptichka); the other six islands are older and high (Por-Bazhyn, Promezhutochnyi, Valter, Kipr, Kvadrat, Toporik).

Altogether 21 soil pits have been studied. Soils on the top positions, in the central parts of islands were chosen as key-profiles to study a general evolutionary trend. These geomorphological positions are presumed to be a starting point of heaving process. Supposedly, tops of islands were the first to emerge above the water table, and, hence, to lose the hydrological connection with the lake when the permafrost table got higher than the lake level. Moreover, top positions were less affected by the seasonal and long-term lake level fluctuations.

Field morphological descriptions including the whole over-permafrost strata were provided for soil pits. Soil description, diagnostics, designation of horizons and classification are given in the WRB system [5, 8].

Micromorphological studies were conducted for key soil pits on old islands. Undisturbed soil monoliths were studied in thin sections under polarizing microscope Nikon E200 Pol in plain polarized (PPL) and cross polarized (XPL) transmitted light at magnifications 40×, 100×, 400×.

Analytical studies were performed using the standard methods [5, 13]: pH was measured in water suspension by potentiometry; total organic carbon – by wet oxidation with dichromate potassium and concentrated sulfur acid in soil organomineral and mineral horizons, in the organic horizons organic carbon content was determined by dry combustion; carbonates were determined after Kozlovskiy; total soluble salts were estimated from electric conductivity measurements in water extract soil : water = 1 : 5; gypsum content was determined in 0.1–0.25 M HCl extract; bulk chemical composition was analyzed by X-ray fluorescence method on the serial spectrometer PW 2400. Phytolith analysis was conducted by Dr. A.A. Gol'eva according to approaches and methods published in [3].

Method of complex group analysis of biological composition supplied with ecological analysis was applied for diagnostics of lake and bog environments. The method was developed by N.V. Korde for lake sediments (gyttja) [9], and later supplemented and successfully approved for other water-related environments (bogs, floodplain sediments and soils, waterlogged soils) [2, 6, 14]. The detailed methodology is published in [12]. Laboratory procedure of complex group bioanalysis includes mixing 0.5–1.0 cm^3 of a native sample with water in proportion 1 : 50, and optical microscopy of the drops of obtained suspension with magnifications of 280–400×. All encountered biological objects (their remains) are identified up to the lowest possible taxonomic level (from order to species). The analysis is concentrated on bio-indicators of water-related environments. The following groups of biological objects were under examination: all algae orders (*Diatomeae, Chrisophyta, Cyanophyta, Chlorophyta* etc.), animals (*Protozoa, Insecta, Spongia, Cladocera, Ostracoda* etc.), vegetative parts of vascular plants, their spores and pollen. In total not less than 500 of individual bio-remains were counted for each sample.

Vascular plant residues were analyzed after washing the preliminary soaked in hot water 20–30 g sample on a 0.25 mm sieve. Oversize rest is set in 2–5% alkali for several hours, and then washed with water on the sieve again. After that, the plant residues free of mineral particles and humus compounds were examined under an optical microscope at 56–80 magnifications. Percentages of different taxonomic groups of residues were estimated visually according to an area taken by residues of every identified taxa in microscopic field.

STUDY SITE

The climate of the study area is ultra-continental subarid with severe winter and relatively hot short summer (the frost-free season is only 32 days long). There is a certain deficit of meteorological data for the study area. In this ultra-continental mountain region every depression has its own climatic features. The meteorological station situated earlier in the trough produced only 5 years of regular observations (1958–1962). So, the short observation period is not enough to reflect representatively the climatic conditions of the area. Nevertheless, basing on these data it is possible to assess the mean annual temperature as –6.1°C, the amplitude of annual temperature variation makes up 55.5°C, the sum of temperatures above +10°C is 1000–2000°. Mean annual precipitation is 230–323 mm, and only 11% occurs as snow [1]. There is no published data available on the seasonal freezing-thawing processes. Continuous permafrost was discovered in the bottom of Terekhol'skaya Trough. It is up to 170 m thick according to geophysical data [10].

Terekhol Lake is situated to the west from the long southwest – northeast axis of the trough. The lake has a considerable area of 33.19 km^2, but is extremely shallow: mean depth is about 0.6 m; less than 1% of the lake area is deeper than 1 m. Islands occupy about 2.85 km^2. There is no permafrost below the lake (talik), but all islands have permafrost: newly formed permafrost occurs at a depth from 0.3 up to 2 m and is 25–30 m thick in the Por-Bazhyn Island.

Preliminary analysis of satellite images from different wavelength has allowed to group islands in terms of their moisture supply and supposed elevations above the lake level. The terrain verification by topographic survey has proved that "wetter" islands are relatively low – <2.5 m, and "dryer" islands are relatively high – >2.5 m, with two of them >4.0 m (these are the largest Por-Bazhin and Promezhutochnyi islands being 0.058 and 0.13 km^2 in area, respectively). The geochronological studies showed that high and low islands compose two groups differing in age (Fig. 1).

The maximal range of the lake level fluctuations registered during three years did not exceed 0.4 m. That means that nowadays the islands are subjected to lake level-related seasonal or inter-annual changes of water regime in their low peripheries. The central elevated parts of the lowest islands in the first altitude-age group and lower parts of the high islands (<1–2 m) can be influenced only by the extreme lake level fluctuations. However, the surfaces above 2 m hardly could be subjected to lake water influence within the last several years.

The lacustrine sediments serve as parent material for island soils. Limnic origin is evidenced both by

Table 1. Complex group biological composition. Profile O-2/2008, Pelikan island (% of bio-residues' sum)

Sampling depth, cm	Vascular plants		Algae			Animals		
	Vegetative parts	Pollen and Spores	*Diatomeae*	*Chrysophita*	*Desmidiales*	*Spongia*	*Protozoa*	*Cladocera*
0–5	69.0	2.0	21.0	4.0	–	0.4	3.6	–
5–10	90.6	0.3	2.8	2.8	–	1.5	2.0	–
10–14	76.0	–	17.7	1.9	0.6	3.8	–	–
14–20	69.0	1.7	27.0	1.1	0.6	–	0.6	–
20–25	32.5	1.4	59.8	4.3	–	1.9	–	–
25–30	35.5	–	56.7	2.1	–	5.3	–	0.4
30–35	22.1	0.3	70.7	6.1	0.3	0.6	–	–
35–40	30.4	0.3	65.1	2.0	0.6	1.4	–	0.3
40–45	23.0	0.3	68.2	7.6	–	0.9	–	–
45–50	38.1	0.3	54.0	7.0	–	0.6	–	–
50–56	55.5	0.4	28.2	13.9	–	1.3	0.8	–
56–60	86.2	–	10.3	3.4	–	–	–	–

their litho-stratigraphy, and the composition of bioremains (Table 1). These are unconsolidated, well stratified deposits including the layers of highly calcareous, reach in organic carbon silts, silty loams, sand and sandy loams, gyttja, peat and marls. The composition of bioremains reliably testifies to the limnic origin of the parent materials. The sediments of both high and low islands contain numerous remains of a wide variety of fresh-water organisms: *Cyanophyta, Diatomeae, Crysophita, Volovocacea, Desmidiales, Chlorococcales,*

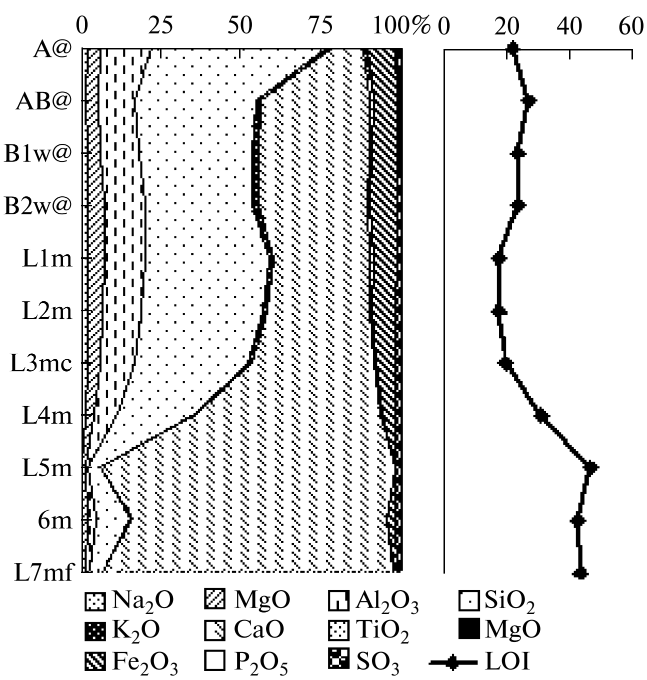

Fig. 2. Bulk chemical composition. Profile T-2, Promezhutochnyi island, p. 7.

Euglenophyta, Spongia, Cladocera, etc. As evidenced from their morphology and composition, these sediments are mostly autochthonous limnic, biochemogenic, rich in carbonates and organic matter with different, but generally not prevailing share of allochthonous, terrigenic (fluvial and aeolian) material, mostly derived of granitoids and limestones. The total content of CaO varies considerably, but it is never less than 20% (on ignited weight). The content of SiO_2 does not exceed 30%, while in marl layers it drops up to the first percents (Fig. 2). The sediments are rich in sulfur: up to 9% of SO_3 on ignited weight. Microscopic studies of fresh lake sediments revealed that originally sulfur is encountered in reduced sulfide form. However, it is oxidized to gypsum in recent soils. These sediments along with prominent vertical stratification are characterized by pronounced lateral facies changes. Therefore, both vertical and lateral heterogeneity is inherent to the parent materials: the carbonates/silicates ratio strongly varies, as well as the contents of organic carbon (both in humus compounds and bioremains) and sulfur.

RESULTS AND DISCUSSION

Young and low islands. The relative altitude of low islands above the lake level is 1–2.5 m. Permafrost depth on the top position in July–August is 0.6–0.7 to 1.5 m (on the islands with sandy strata above permafrost). The permafrost table on the top geomorphological level is higher than the lake level, so that soils are well drained, and are not subject to inundation. In some islands (Dalnii, Ptichka) the permafrost table in the upper topographic level appeared to be comparable with the measured altitude above the lake level. Nevertheless, the soil profiles are drained and have no over-permafrost water. This is a transitional case: even insignificant fluctuations of the lake level can re-establish a hydrological connection of these soils with the lake and restore waterlogging.

Nine radiocarbon dates were obtained from the base of organic layers overlying mostly mineral strata of lacustrine sediments. The dates are evenly distributed in the range 400–1700 cal yrs BP. During this period shallow areas of the lake bottom appeared, but the islands have not yet emerged, or at least were subject to seasonal inundation. The terrestrial peat, indicative of the subaerial environment, was identified only in the upper 10–15 cm in soils of low islands where peat horizons are well stratified. The radiocarbon dates from the base of this terrestrial peat are <200 yrs. BP. According to aerial photos made in mid-1950-ies, all low islands already existed. Therefore, the islands got to the phase of relatively stable subaerial development most probably during 18–19th centuries, i.e. during the Little Ice Age period.

The plant communities of low islands in their central, elevated parts are mostly meadow grass-herbaceous (with *Calamagrostis* sp., *Chamerion angustifolium* (L.) Holub, *Rumex crispus* L., *Senecio nemorensis* L., *Erysimum* sp. being dominants). In most of islands single trees (birch, rarely larch) and willow bushes occur. Other islands, where over-permafrost sediments have sandy layers (Nevezeniya, Ptichka islands), are covered in their tops with open crooked birch forest with wild black currant and willow, the lower canopy dominated by grasses with minor participation of herbs (*Calamagrostis* sp., *Poa* sp., *Heteropappus altaicus* (Willd.) Novopokr., *Tanacetum vulgare* L., *Artemisia dracunculus* L., *Chamerion angustifolium* (L.) Holub).

In Dalnii island, the hillocky sedge fens were recently replaced by willow-herb grass communities. This is obvious from well preserved hillocky microtopography (Fig. 3a). Generally all mentioned plant communities described in the top positions of low islands correspond to the well balanced moisture conditions: there are no over-moistening and no over-drying nowadays.

The Histic Turbic Cryosols or (rarely) Cryic Limnic Histosols were found in the top positions of young low islands.

The histic layer in soils with high permafrost table, under grass-herbaceous vegetation is clearly stratified. It is usually subdivided into three – four horizons different in their morphological characteristics: color, organic residues decomposition rate, abundance of mineral admixtures (mostly shells and shell fragments), and botanical composition of plant residues. The upper horizons are nearly pure organic, and commonly reveal signs of destruction. Sometimes, there are soft ferruginous tubes along root channels in the middle and lower part of the histic layer. Histic horizons are underlain by highly calcareous limnic material. A description of a typical soil is given below.

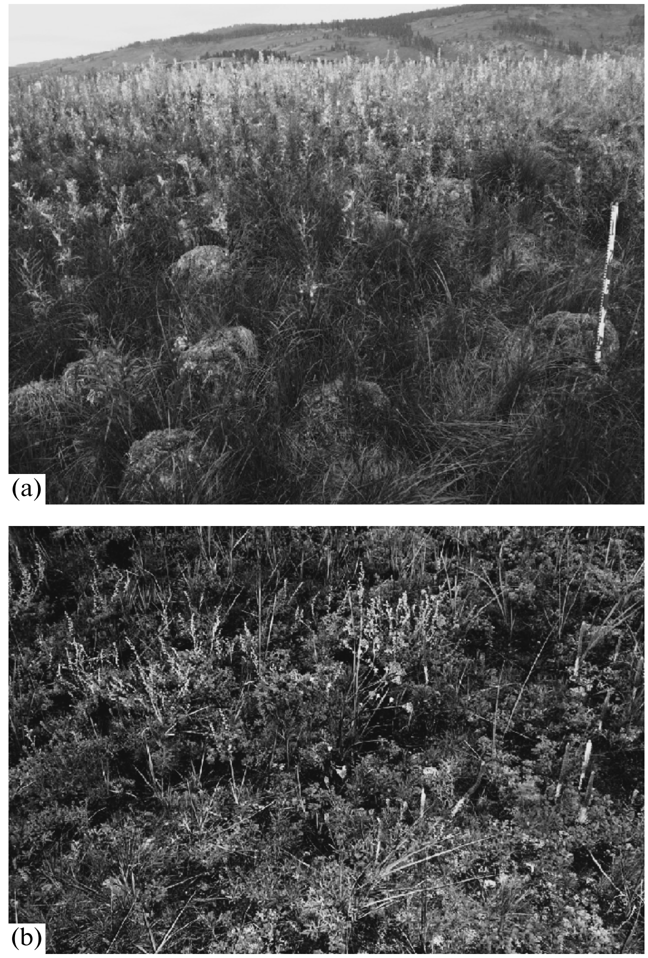

Fig. 3. Patterns of surface of island soils: (a) Dalnii island, residual sedge tussock, pit 9; (b) Promezhutochnyi island, Polygonal net of open cryogenic cracks, pit 14.

The Pelikan island, profile PB-08/O2, 50.64913°N, 38.948' 97,42090°E, altitude above the lake level is 1.2 m. Permafrost table is at the depth of 0.6 m (23.08.2008).

Hi, 0–14 cm. Very dry, light grayish-brown peat with minor admixture of mineral material, low degree of decomposition. Evidently destructive: loosened, disintegrated, inelastic, hay-lake. There is a 1-cm-thick band of poorly decomposed platy fragments of plant residues at a base of the horizon (probably *Typha* sp.).

Ha, 14–40 cm. Dry, dark grayish-brown, strongly decomposed humified peat, with considerable admixture of mineral material. Yellowish-brown soft accumulations of iron oxides along thin root channels.

He, 40–56 cm Weakly moist, very dark grayish-brown peat, a share of mineral admixture is considerable and increasing downwards. The degree of decomposition varies from moderate to moderately strong. Residues of *Carex* sp. were identified in the bottom part of the horizon. Effervescence with the hydrochlo-

Table 2. Composition of bio-residues in oversize rest from 0.25 mm sieve. Profile O-2/2008, Pelikan island (% of bio-residues' sum)

Sampling depth, cm	*Cyperaceae*	*Gramineae*	*Phragmites communis*	*Typha*	*Camarum palustre*	*"Lythrum"*	*Bryales*	*Sphagnum*	*Potamogeton*	*Ceratophyllum*	*Nymphaeaceae*	*Myriophillum*	*Gloeotrichia*	*Chara*	*Spongia*	*Cladocera*	*Bryozoa*	*Ostracoda*	*Mollusca*	Unidentified plant residues
0–5	20	10	–	–	*[2]	–	–	–	–	–	–	–	–	–	–	–	–	–	–	70
5–10	40	20	–	*	*	*	–	–	–	–	–	–	–	–	–	–	–	–	–	40
10–14	20	10	10	10	*	*	–	–	*	*	–	–	–	–	–	–	*	–	–	50
14–20	–	–	*	*	*	–	–	–	*	20	–	–	–	–	*	*	–	–	–	80
20–25	–	–	–	*	–	–	*	–	5	60	–	–	*	*	*	*	–	–	–	35
25–30	–	–	–	*	–	–	*	–	*	45	*	–	–	*	–	*	–	–	–	55
30–35	–	–	–	10	–	–	*	–	–	40	–	–	–	–	–	*	–	–	–	50
35–40	–	–	–	5	–	–	*	–	*	55	–	–	–	–	–	*	*	–	–	40
40–45	–	–	–	5	–	–	10	–	*	20	–	*	*	*	*	*	–	*	–	65
45–50	10	–	–	–	–	–	5	–	–	15	–	–	–	–	–	*	–	–	–	70
50–56	–	–	–	–	*	*	–	*	–	–	–	–	–	*	–	*	*	–	*	100
56–60	–	–	–	–	–	–	*	–	–	*	–	–	–	*	–	*	–	*	*	100
58–61	–	–	–	5	*	*	*	–	–	30	–	–	*	–	–	–	–	–	*	65

Note: [2] Sporadic finds of bio-residues.

ric acid starts at 45 cm. Shell detritus appears close to the lower border. Cryoturbated at the lower boundary.

Lml, 56–60 cm Slightly moist, light yellow to olive yellow limnic marly silt with lenses and irregularly shaped fragments of overlying very dark grayish-brown peat. Clear schlieren cryogenic structure with iron oxides impregnation along horizontal surfaces.

Lmf, 60–72 cm Icy permafrost with developed Schlieren structure. Dark bluish-grey silt loam with intruding wedges of overlying material.

Complex group quantitative biological composition of the over-permafrost soil-sedimentary profile demonstrates that the whole section was formed in a lake or lake-related environment since there are numerous and variable residues of freshwater organisms in every sample (Table 1). A certain accumulation of lake material on the top of island took place even in the very last phase of peat formation. The upper H horizon still contains considerable amounts of *Diatomeae* and *Crysophita* as well as *Spongia*. That was most probably possible due to inter-annual or seasonal rises of the lake level and inundation of the island when it was insignificantly uplifted above the water surface. Actually, a fluvic qualifier can be given to the uppermost part of the profile. At present, accumulation of limnic material on the top of this soil is completely impossible because of its considerable relative altitude, which cannot be reached by lake waters because of weak fluctuations of the lake level.

The data on the composition of bio-residues left on the 0.25 mm sieve for this profile (Table 2) enable us to conclude that only the upper H horizon is real, terrestrial sedge-grass peat. Lower organic layers identified as peat according to their morphology (Ha and He), actually appeared to be lake detrital gyttja-peat composed mostly of lacustrine plant residues (*Ceratophyllum demersum*) with participation of bog plants resistant to long-lasting waterlogging and to partly submerged survival (*Phragmites communis, Typha, Comarum palustre*). In terms of WRB, this part of the profile can be qualified for Subaquatic Histic horizon.

The proportion of unidentified residues within a botanically and morphologically uniform layer of the upper terrestrial peat can be considered as an indirect characteristic of its destruction. It is irregular within the horizon having the maximum (70%) in the uppermost 5 cm. This testifies to a relatively recent break of peat accumulation and beginning of its decay. The peat destruction was induced by the disruption of lateral hydrological connection with the lake water owing to a progressive heaving and the elevated permafrost table above the lake level (and/or probable climatically induced drop of the lake level lower than the permafrost table).

Taking into account all the facts we classified this profile as Cryic Fibric Limnic Histosol (Calcaric, Turbic, Drainic, Epifluvic).

Soils of other low islands (Nevezeniya, Ptichka) with the above-permafrost coarse-textured sediments (sand to sandy loam), rather deep permafrost table, under sparse forest vegetation differ from the above described soils in terms of morphology and composition of their H horizons. Organic and organomineral horizons occur only in the upper 15–20 cm here.

Table 3. Chemical characteristics of soils

Horizon	Depth, cm	pH	C org	$CaCO_3$	$CaSO_4 \cdot 2H_2O$	Sum of soluble salts
			%			
Profile T-2/07, 50.61806°N, 97.38964°E. A relative altitude above the lake level is 4.4 m, permafrost table from 1.5 m (05.07.2007)						
A@	0–15(23)	7.65	9.26	2.59	0.02	0.11
AB@	15(23)–27(33)	8.15	5.26	28.06	0.01	0.11
B1w@	27(33)–40	8.0	3.94	33.78	0.68	0.47
B2w@	40–50(60)	7.9	3.82	33.51	2.67	1.17
L1m	50(60)–68(78)	8.3	2.43	32.05	1.29	0.85
L2m	68(78)–88(98)	8.15	2.19	33.19	4.80	1.26
L3mc + L4m	93(102)–106(115)	8.0	2.33	37.86	1.92	1.17
Profile PB-09/O-13, 50.60707°N, 97.37117°E, the relative altitude 4.4 m, permafrost table from 1.50 m (13.08.2009)						
He	0–15	8.2	63.34[3]	1.50	no data	no data
Hak@	15–2(25)	8.6	8.23	12.30	no data	no data
BCg@	20(25)–35(62)	9.0	1.04	28.35	no data	no data
Lm@	36(62)–80(90)	8.95	0.52	26.99	no data	no data
Lm@	80(90)–150	9.0	0.37	31.17	no data	no data

Note: [3]LOI, %

These are two horizons which differ in organic matter decomposition level (moderate to moderately strong). Both H horizons contain a considerable admixture of mineral material, silicate sand particularly, and do not reveal obvious destructive features (or they are poorly developed). The lower H horizons have whitish mottles or veins of secondary carbonates.

Most of bio-residues in peat horizons of these soils are unidentifiable (85–95% of the 'bio-remains'), that may be possibly explained by better conditions for mineralization in a coarser textured, better aerated material, and/or by some longer period of the subaerial development of these soils. Complex group biological composition and the composition of residues >0.25 mm in H horizons include a variety of lake and lake-related indicators. Algae (*Diatomeae* (*Hantzschia, Pinnularia* sp.), *Crysophyta, Chara*), and water animals (*Cladocera, Ostracoda, Bryozoa, Pisces* – scales of fish) were recorded among the residues of lacustrine organisms here. There are also residues of water-bog plants tolerant to a long-term waterlogging: *Comarum palustre, Phragmites communis, Typha* sp. But there is no horizon of terrestrial peat, or at least the one with recorded findings of terrestrial environment indicators. This presumes the absence of the phase of terrestrial peat accumulation on sandy islands because of higher rates of islands uplifting, and permafrost level descending. The last one can be reasoned by a higher thermal conductivity of sands.

Some analytical data were obtained for soils of young islands on sandy components of limnic material (Table 3). The upper He horizon reveals high loss on ignition (63.34%). This is mostly organic loss, since CO_2 of carbonates makes up only 1.5% in this horizon.

The next horizon was also qualified for H in spite of insufficient percentage of total organic carbon according to WRB criterion (8.23%). The reasons were the morphology of this horizon (first of all a considerable part of weakly decomposed plant residues), and its complex biological composition (bio-indicators of water-related environment) described above.

The soil is alkaline to strongly alkaline with pH values increasing down the profile. The top horizon is leached off from carbonates. Slightly irregular distribution of carbonates in the mineral part of the profile is attributed to the lithological discontinuity.

The presented facts allow considering the soils on sandy islands as a product of successive phases of soil formation synchronous to sedimentation in bog-lake environment, and related to the initial phase of heaving process which gave place to a subaerial phase of initial automorphic pedogenesis under well equilibrated moisture conditions allowing tree growth. This last, present-day phase comprises mineralization of limnic organic matter, thus its implication in organic carbon exchange, accumulation of pedogenic humus material, obviously different in composition under meadow and forest plant communities; start of carbonates leaching. The soils on tops of sandy islands were classified as Histic Turbic Cryosols (Calcaric, Drainic, Limnic).

Older and high islands. Islands of the second altitude-age group have the relative altitude above the lake level more than 2.5 m; the permafrost depth in August is about 1.5–2 m. Therefore, soils are totally isolated from lake waters and not inundated or waterlogged at present. Significant springen-dash early summer surface excessive moistening is hardly possible also due to general climatic aridity and annual distribution of precipitation: snow melt and slow seasonal frost thawing do not give much additional water owing to soil dryness during freezing and very restricted amount of snow. Maximal registered frontal depth of rain water percolation is about 30–40 cm. The convex permafrost table inducing perfect downslope drainage prevents considerable moistening above the icy permafrost in summer. Thus, the existing soil conditions do not favor the development of hydromorphic features.

The age of high islands was estimated by radiocarbon dating of plant fragments from a distinct stratigraphic layer found at depth of 1.3–1.7 m in different islands. Extrapolation of sedimentation rates obtained in lacustrine cores up to the surface gives an estimate of sedimentation break (=emergence of islands) at about 4000–5000 cal yrs BP. Those is supported by the results of microfossil and bulk chemical analyses that correlate well with that of lacustrine cores.

Central elevated parts of older islands are occupied by dry steppe phytocenoses with feather grass and wormwood participation. Main dominants are *Stipa* sp. L., *Poa arguneusis* Roshev., *Bromopsis inermis* (Leyss.) Holub, *Psathyrostachys hyalantha* (Rupr.) Tzvel., *Veronica incana* L., *Orostachys spinosa* L., *Bupleurum scorzoneri-folium* Willd., *Artemisia* sp., *Heteropappus biennis* (Ledeb.) Tamamsch. ex Grub.

A description of typical soil on the top of high island is presented below.

Promezhutochnyi island, profile T-2/07, 50.61806°N, 97.38964°E. A relative altitude above the lake level is 4.4 m. Permafrost table is at the depth of 1.5 m (05.07.2007).

The surface has a polygonal net of closely spaced (0.3–0.4 m), medium wide to wide, very deep (up to 0.8 m) open cracks (Fig. 3b).

A, 0–15(23) cm. Very dry silty loam, very soft, very dark brownish black. Structure is moderate very fine granular, weak fine to medium subangular blocky, with prismatic elements. Visible effervescence with HCl starts at 10 cm. Clear, irregular boundary with deep pockets.

AB, 15(23)–27(33) cm. Very dry silty loam, soft and light, dark grayish-brown. Structure is weak, fine to medium, angular to subangular blocky with prismatic elements. Strong effervescence. Clear irregular boundary with pockets and wedges (up to 40 cm deep).

Blw, 27(33)–40 cm. Dry silty loam, brown, nonclearly laminated and mottled: brownish blue-gray, brown, light bluish-gray wavy laminae, lenses and mottles. Moderate angular blocky to prismatic medium-size structure. Strong effervescence. Boundary is gradual, wavy.

B2w, 40–50(60) cm. Dry silty loam. Blue-gray with diffuse light gray and dark bluish-gray mottles; indistinct 1–2 mm thick, dark bluish-gray and brownish wavy laminae. Structure is moderate to strong, fine to medium-size, with angular blocky-prismatic peds and indistinct schlieren. Very strong effervescence. Clear wavy boundary with small irregular tongues.

L1m, 50(60)–68(78) cm. Dry to slightly moist strongly calcareous limnic silt, light brownish-yellow with diffuse grayish-yellow and whitish-yellow mottles. Weak coarse blocky-prismatic structure. Clear, broad-wavy inclined boundary.

L2m, 68(78)–88(98) cm. Slightly moist, strongly calcareous, clearly laminated: fine interstratification (1–4 cm) of brownish-gray, light brownish-gray, grayish-brown and whitish laminae of silt and silty loam. Few, soft, fine (<5 mm) iron oxide segregations (nodules). Very weak coarse angular blocky structure. Clear broad-wavy inclined boundary.

L3mc, 93(102)–92(112) cm. Slightly moist strongly calcareous fine sandy silt, laminated, grayish-brown with laminae and mottles of humified and peat-like organic matter. Abrupt transition, broad-wavy inclined boundary.

L4m, 92(112)–106(115) cm. Slightly moist extremely calcareous silt, powdery, with shell detritus, light brownish-gray. Abrupt transition, broad-wavy inclined boundary.

L5m, 106(115)–135(141) cm. Slightly moist, laminated off-white pure marl with interlayers of coarse well preserved plant detritus (*Thypha*), crumb structure, extremely loose. Abrupt transition, broad-wavy inclined boundary.

L6m, 142(146)–150(155) cm. Dry extremely calcareous silt, rich in shells and plant detritus, light grey, very loose. Abrupt transition, broad-wavy inclined boundary.

L7mf, 150(155)–170 cm. Frozen light brown extremely calcareous silt with shells and plant detritus and diffuse lamination.

The most characteristic features of these soils are their top horizons. They are very dark, brownish-black, or blackish-brown (10YR2/3 to 5YR2/3), very loose horizons (bulk density is 0.75–0.81 g/cm^3) with high to very high contents of organic carbon (7–18%), weak structure with clear blocky or prismatic elements. Sometimes strong to medium very fine granular structure is observed as a low structural level. Actually these horizons have got diagnostic features getting between histic and mollic qualifiers, at the same time they have glossic and turbic features. The underlying B horizons reveal only angular blocky-prismatic structure and more or less developed turbic features interpreted as pedogenic ones. Obviously, the pedogenic concentrations of carbonates, gypsum or readily soluble salts were not identified. Limnic material occurs below B horizons. Lacustrine sediments are well stratified in color, laminated within stratigraphic units, presence and character of organic matter (peat laminae and mottles, plant residues), content of carbonates, texture (mostly in the content of sand fractions).

The micromorphological studies revealed a number of features important in terms of genesis and evolution of these soils. Even A horizon contains primary (lithogenic) calcite as shell detritus and sand-size grains of marbles. Primary calcite is obviously unstable here: it is often re-crystallized, plasma is nearly free of calcite impregnation. Various forms of secondary carbonates appear in B horizons and below them: coprolites with micritic calcite impregnation, incrustations of plant residues, calcite pseudomorphs on plant tissues (Fig. 4a), nodules (Fig. 5), few coatings, infillings in cryogenic fissures. Micrite is prevalent, although sparitic calcite also occurs. Micritic (often residual) inter-aggregate impregnations occur in horizons with developed hydro-cryogenic ooid structure (Fig. 6). The B horizons reveal very strong calcitic impregnation of plasma, which is maximal in the profile. All this testifies to the processes of both intra-horizontal and vertical inter-horizontal redistribution of carbonates in the profile with general leaching (eluvial) trend.

Gypsum accumulations were revealed under the microscope in B horizons and below. These are concentrations of very fine crystals (0.05–0.2 mm) in pores. Gypsum doesn’t occur in lacustrine sediments obtained from bottom cores, whereas sulfides were found there. Occurrence of sulfur in oxidized form of gypsum and its pore localization in soils testifies to the pedogenic gypsum accumulation. Micritic pseudomoprhs over gypsum crystals sometimes occur in B horizons.

Strong iron oxides pigmentation of plant residues is observed throughout the profile. Ferruginous mottling evidences a former soil hydromorphism in mineral horizons (Fig. 4b).

Thus, we consider the following micromorphological features indicative of pedogenesis in waterlogged environment: ooidal structure and micritic inter-aggregate impregnation, incrustations of plant residues, pseudomorphs over plant tissues, micritic nodules (optionally they can be lithogenic), pore accumulation of fine gypsum crystals, iron oxides pigmentation on plant residues, redoximorphic mottling. At the same time, we regard the signs of primary carbonates instability, weak calcite impregnation and impoverishment in gypsum registered in A horizons, along with strong calcite impregnation of plasma and coprolites in B horizons, micritic pseudomorphs over gypsum crystals, sparite nodules, coatings, calcite infillings in cryogenic fissures, re-crystallization of primary carbonates as manifestations of the last phase of pedogenesis in well drained conditions under dry steppe vegetation.

The analysis of complex group composition and composition of bio-residues in oversize rest from a 0.25 mm sieve was carried out for three soil profiles on the top positions of Valter, Kvadrat and Promezhutochnyi islands. Organic matter is well humified there

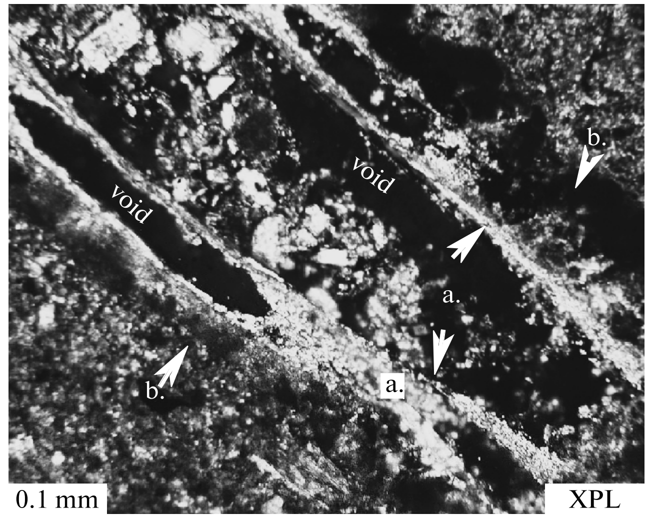

Fig. 4. Residues of plant tissue: (a) calcite pseudomorphs of plant tissues, p. 17; (b) Strips of iron oxides' mottling, p. 17.

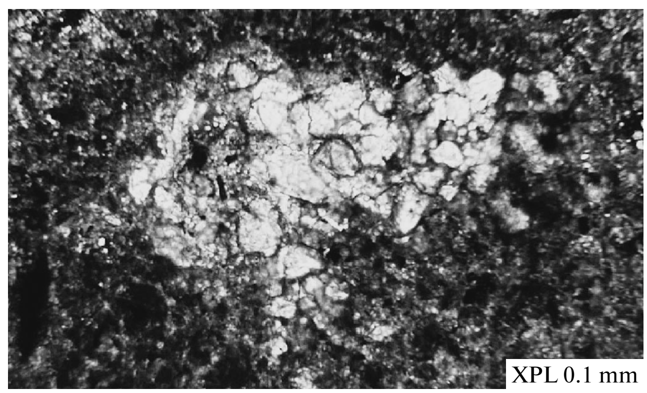

Fig. 5. Sparitic nodule, p. 17.

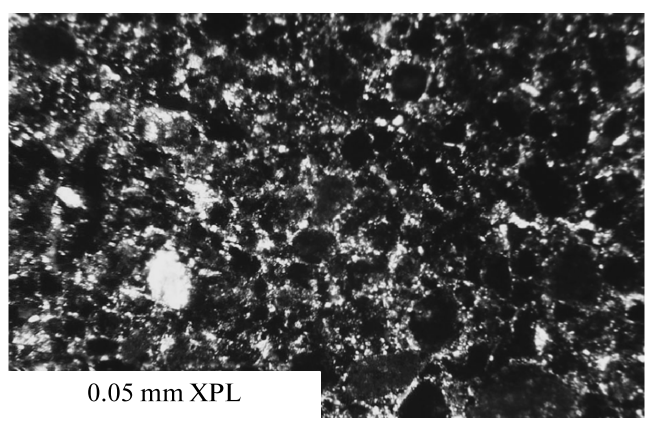

Fig. 6. Ooid microstructure and residual micritic interaggregate impregnation, p. 17.

Table 4. Complex group biological composition and composition of bio-residues in oversize rest from 0.25 mm sieve. Profile T-2-08, Promezhutochnyi island

Sampling depth, cm	Composition of bio-residues > 0.25 mm, (% of bio-residues' sum in oversize rest from a 0.25 mm sieve)									Complex group bio-composition, % of bio-residues' sum	
	Carex	*Phragmites communis*	*Calamagrostis*	*Camarum palustre*	*Drepanocladus*	*Typha*	*Chara*	*Mollusca*	Unidentified plant residues	Vascular plants	*Spongia*
0–4	–	*[4]	–	–	–	*	–	–	100	99.9	0.1
4–8	5	–	*	–	*	*	–	–	95	99.9	0.1
8–13	5	–	5	*	–	–	–	–	90	99.7	0.3
13–19	5	–	*	*	–	–	–	*	95	99.7	0.3
19–25	–	–	*	*	–	–	–	10	90	99.0	1.0
25–30	–	–	–	–	–	–	5	50	45	99.0	1.0

Note: [4] Sporadic finds of bio-residues.

due to a long-term development in drained conditions. So that in majority of samples most of residues of vascular plants are got to a category of "unidentified" which makes up to 90–100% of all residues >0.25 mm, and most part of organic residues of water-related organisms are obviously lost due to humification. Besides that, organomineral horizons are actively bioturbated in steppe landscapes, non organic bio-remains such as spicules of *Spongia*, shells of *Diatomeae* and *Ostracoda* etc. can be masked by humus coatings. All this actually means that the original biological composition in well-drained soil environment is distorted by destruction and other processes and does not allow accepting the results as quantitative characteristic of ecotopes, and trace in details the evolutionary trends for soil profile and local landscape. However, finds of lake or paludous environment residues allow drawing a conclusion on the genesis of parent material and former stages of soil evolution.

First of all, complex group biological composition of all profiles confirms the lacustrine origin of the parent material by presence of a variety of freshwater organisms' residues. At the same time, a wide spectrum of plants related to paludous environment was recorded in organomineral topsoils. These are *Typha, Comarum palustre, Phragmites communis*, *Calamagrostis* sp., *Carex, Sphagnum* sp., *Sphagnum magellanicum, Drepanocladus* (as an example the results for the organomineral part of the profile T-2/07 are presented in Table 4). In addition, numerous phytoliths of hygrophytes such as reed (*Phragmites communis*) and meadow grasses were recorded by the phytolith analysis all over the top horizons of these soils. All these data definitely prove that local landscapes and soils of high older islands passed the stage of post-sedimentary soil hydromorphism.

Some chemical characteristics of soils on high older islands were obtained for the profile T-2/07 (Table 3). The content of total organic carbon is very high in A and AB horizons (9.26 and 5.26%, respectively). Mineral horizons reveal also considerable amounts of organic carbon, which is definitely related to limnic origin of parent material. The profile demonstrates alkaline reaction with lower pH values in the A horizon. In spite of micromorphologically registered presence of primary calcite, the top horizon contains only small amounts of carbonates as compared to lower extremely calcareous horizons. So, the upper part of the profile is leached of carbonates. The organomineral part of the profile contains only traces of gypsum. Its accumulation is observed in the B2 horizon and deeper. The soil is saline: the sum of readily soluble salts reaches 1.17–1.27% in the B2 horizon and in the underlying layers of limnic material. The upper part of the profile contains only small amounts of readily soluble salts.

Thus, the recent soil has got strongly accumulative, relatively shallow humus profile, alkaline pH, eluvial type of carbonates pattern, gypsum and readily soluble salts. These analytical characteristics are in good agreement with the current conditions of pedogenesis: precipitation deficiency, perfect drainage, steppe vegetation, a deep active layer.

Taking into account all obtained data the soils developed on top positions of high, older islands can be classified as Calcic, Episalic, Molliglossic, Turbic Cryosols (Gypsiric, Calcaric, Limnic). Application of both Calcaric and Calcic qualifiers is conditioned by the presence of both primary (lithogenic) and secondary (pedogenic) carbonates actually in any horizon (in some profiles with the exception of the top A horizon).

Thus, the whole complex of above data allows to conclude that soils of the high older islands were also formed on lacustrine sediments, which were moved above the lake level by frost heaving 4000–5000 years ago. These soils definitely have survived the paludous stage of hydromorphism in the very beginning of their development, which was recorded in the biological composition of their organo-accumulative horizons (presence of paludous plants' residues and phytoliths), in their morphological properties, namely, dark brownish-black color and specific granular-subangular-blocky structure with prismatic elements, as well as in their micromorphological features (ferruginous mottling, and impregnation of plant residues; incrustations and pseudomorphs over plant tissues; ooidal structure and micritic inter-aggregate impregnation, pore accumulations of fine gypsum crystals). The recent phase of pedogenesis in well-drained steppe environment reworks and partly erases the lithogenic and paleohydrogenic heritage of these soils and leads to generation of the Calcic Molliglossic Cryosols profile corresponding to the present-day conditions.

CONCLUSIONS

The studies of highly specific soils developed on cryogenic islands of two generations in the Terekhol Lake, formed during two Late Holocene phases of heaving processes activation, allowed to reconstruct the major evolutionary trends for these rather exotic landscapes and their soils; the following phases were identified.

1. Sedimentation of lacustrine marly silts and loams, sandy silts and loams, marly gyttja, marls at the lake bottom.

2. Beginning of frost heaving: appearance of shallow spots, followed by emergence of periodically inundated bottom surface, accumulation of detrital peaty gyttja composed mostly of lacustrine plant remains with participation of water-bog plants tolerant to prolonged inundation (*Typha, Sphagnum, Comarum palustre, Phragmites communis*). Initial stage of synsedimentary soil formation results in the development of Histi-Subaquatic Cryosols Calcaric, Limnic. Nowadays, similar soils are found in a periphery of young low islands.

3. Further heaving, final emergence of the islands above the lake level, terrestrial peat formation with periodical inundation and accumulation of limnic material on the top of the emerged islands. Development of Subaquatic Histic Cryosols Calcaric, Limnic. This phase seems to be very short, and it may be missing in sandy islands.

4. Further heaving caused rise of the permafrost table above the lake level, disruption of lateral hydrological connection of the soils with the lake, better drainage, and decrease of peat accumulation, replacement of paludous vegetation by meadow phytocenoses (sandy islands were forested by sparse crooked birch). Peat degradation, and leaching of the upper horizons started. Histic Turbic and then Calcic Histic Turbic Cryosols (or Cryic Histosols) (Calcaric, Drainic Limnic) were formed. The uplifting coupled with the degradation of thermo-insulating histic horizons contributed to the growth of seasonal thawing depth.

5. Further uplifting induced descending the permafrost table, replacement of meadows or sparse forests by dry-steppe vegetation. Further mineralization of peat topsoils and accumulation of mull-moder humus, leaching of carbonates, gypsum and soluble salts resulted in the formation of Calcic, Episalic, Molliglossic, Turbic Cryosols (Gypsiric, Calcaric, Limnic).

The described particular case of pedogenesis on lake islands uplifting due to frost heaving represents actually a rare phenomenon of cryo-geomorphological evolution, when changes in soils are induced by cryogenic process changing the topographic, hydrological and vegetation factors. In terms of genesis and evolution, the landscapes of cryogenic islands can be considered to a certain extend to be homologues of relatively well studied alas systems in Yakutia – specific thermokarst landscapes including complicated combination of lakes, wetlands and elevated steppe-like sites [4].

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